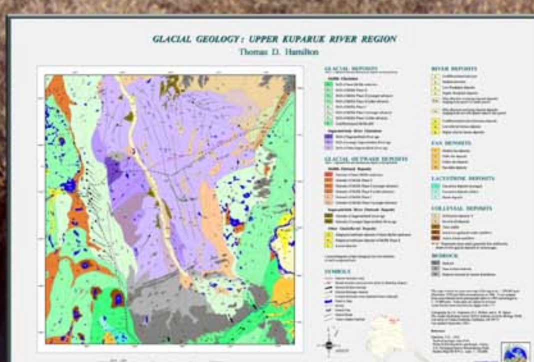
Glacial Geology *of the* Toolik Lake *and* Upper Kuparuk River Regions

by Thomas D. Hamilton



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GLACIAL GEOLOGY OF THE TOOLIK LAKE AND UPPER KUPARUK RIVER REGIONS

By Thomas D. Hamilton

A Contribution to the Geobotanical Atlas of the Kuparuk River Region

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EDITOR

Donald A. Walker

2003

Editors Preface

The terrain of the Upper Kuparuk river region is of major scientific importance because of its proximity to the Toolik Lake Field Station. The 751 km^2 area surrounding the station has glacial deposits left by several major late Cenozoic glaciations. These deposits have a defining influence on the character of the vegetation, the chemistry of stream waters and a wide variety of other terrestrial and aquatic ecosystem characteristics. This map and report are a synthesis of ’s many years of work in the region, and are major contributions to our understanding of its history and ecology.

The mapped information is part of a hierarchical geographic information system (HGIS) that has been assembled for the Toolik Lake Geobotanical Atlas. The HGIS is designed to address research topics at scales ranging from that of individual plant communities to the global ecosystems. At each scale the HGIS contains several data layers including vegetation, hydrology, topography, glacial geology, percent water cover, geomorphology, surface geology, and remotely sensed spectral information. Forthcoming publications will present other maps from the Toolik Lake region.

The decision to publish this work as a Biological Paper of the University of Alaska (BPUA) requires some explanation. This project was designed to add a glacial geology layer to the Toolik Lake Geobotanical Atlas. Late in this project, Dr. Hamilton began work on another report for the State of Alaska Division of Geological and Geophysical Surveys, which included the area of this report plus a larger surrounding area (Hamilton 2003). This BPUA and the DGGS publication were scheduled to go to press over a year ago. Once I learned of the DGGS report, I decided to withhold hard-copy publication of this report because of budget considerations, and the DGGS report was slightly more current and covered a larger area. Instead, I posted the draft of the BPUA on the web site of the Alaska Geobotany Center.

Since then, there has been considerable demand for hard-copy versions of Dr. Hamilton’s map. There have also been delays in publication of the DGGS report caused in part by its upgrade to a Professional Report. With support from NSF, I have decided to go forward with this publication. Although there is some duplication in the BPUA and DGGS reports, this one serves several special purposes. First, the base map for this report is at a larger scale than that of the DGGS report (1:25,000 vs. 1:63,360). This is more appropriate for many site-specific studies associated with study plots or detailed soils and vegetation maps. Second, the scale, frame and layout for this map correspond to other elements of the Toolik Geobotanical Atlas. All the layers in the Toolik Lake GIS, including this glacial geology layer, are registered to an orthophoto topographic base map, which was specially prepared for this project. Finally, the text has been specifically written for the area covered in this report. Future updates, including information from the DGGS report, will be available in digital form from the Alaska Geobotany Center website http://www.geobotany.uaf.edu/arcticgeobot, or the Arctic Data Coordination Center, Boulder, CO, http://arcss.colorado.edu/data/arcss.

Funds for this publication were provided by grants from the National Science Foundation, including OPP-9981914, OPP-0120736, and DEB 9810222.

D.A. (Skip) Walker

March 22, 2003

GLACIAL GEOLOGY OF THE TOOLIK LAKE AND UPPER KUPARUK RIVER REGIONS

By Thomas D. Hamilton

Cover photo: Actively collapsing south-facing flank of kettle shown in inset photo. Combined height of headwall and underlying flow lobes is 23 meters. Open tension cracks are associated with steps on upper headwall and also extend 5-6 meters inland from its crest. Helicopter (back cover) provides additional scale. Photograph taken on 6/19/01 by author.

Inset photo: Aerial view north across the kettle in drift of Itkillik II age, 7.6 kilometers north of Toolik Lake. Deep-seated collapse of its northflank suggests that kettle is actively enlarging through meltout of buried glacial ice. Aerial photograph taken on 6/29/01by author.

ABSTRACT

Glaciers of middle and late Pleistocene age flowed into the upper Kuparuk map area from the west, east, and south. Glacial deposits are assigned to the Sagavanirktok River (middle Pleistocene) and Itkillik I and II (late Pleistocene) glaciations of the central Brooks Range glacial succession. During the initial (maximum) advance of Sagavanirktok River age, large valley glaciers flowed north along the Itkillik, Sagavanirktok, and Kuparuk River drainages. Moraines are massive but subdued, with heavy loess cover and broad flanks smoothed by solifluction. A subsequent less extensive advance of Sagavanirktok River age overflowed into the upper Kuparuk drainage from the west and south, forming moraines and outwash remnants that are intermediate in appearance between those of the maximum advance and the subsequent Itkillik moraine succession.

Itkillik I glaciers abutted divides west, east, and south of the upper Kuparuk drainage, but overflowed those divides only locally. Their moraines are modified by weathering and erosion, but on a much smaller scale than deposits of the Sagavaniktok River glaciations. Crests are slightly flattened, with loess and vegetation cover locally absent; kettle lakes are common. The subsequent Itkillik II advance, which dates between about 25 and 11.5 ka (thousand ^{14}C years B.P.), is marked by little-modified moraines with stony crests and steep flanks. Glacial flow patterns were generally similar to those of present-day river drainage. Two major advances of Itkillik II age took place between about 25 and 17 ka, forming extensive ice-stagnation features around Toolik Lake. A subsequent readvance is dated between about 12.8 and 11.4 ka at its type locality near the east end of Atigun Gorge.

Surficial deposits of Holocene age, although less extensive than those of Pleistocene glaciation, are locally significant. They include alluvial terraces along the Sagavanirktok River, fan deposits at the mouth of the Atigun River, raised beaches and fan-delta deposits around Galbraith Lake, and local landslides and debris flows.

Keywords: Brooks Range, glacial sequence, moraines, outwash, ice stagnation, surficial geology.

ACKNOWLEDGEMENTS

My initial surficial geologic mapping in the region that includes the upper Kuparuk River was supported by the Trans Alaska Pipeline System (which later became the Alyeska Pipeline Service Company) in 1969-72 and by the U.S. Geological Survey (USGS) in 1975-76. Robert M. Thorson provided capable field and office assistance during the USGS mapping project. The more detailed subsequent mapping of the upper Kuparuk River area for this report was supported in 1996-97 by D.A. (Skip) Walker through the National Science Foundation's Land-Atmosphere-Ice-Interactions' FLUX and ATLAS projects, and the Toolik Lake Long Term Ecological Research project. Cartographic and GIS support were provided by Jim Anderson at University of Colorado and Andrew Balser of the Alaska Geobotany Center, University of Alaska, Fairbanks. Christine R. Martin and Jamie Hollingsworth executed the layout for the publication. Thorough reviews by John Hobbie and Darrell Kaufman contributed significantly.

GLACIAL GEOLOGY OF THE TOOLIK LAKE AND UPPER KUPARUK RIVER REGION

INTRODUCTION

The complex glacial deposits in the upper Kuparuk River area (Plate A) reflect the interaction of glaciers that flowed into the area from three separate ice sources (Figure 1). Ice flowed northeastward from the Itkillik River valley into the upper Kuparuk River drainage; separate glaciers entered the area from the Sagavanirktok River valley to the east and from the Atigun River Valley to the south and southeast. This flow regime, which differed in detail with each glacial advance, was controlled in part by tectonism. The upper Kuparuk River region is situated at the boundary between the central Brooks Range, which had become tectonically stable by late Cenozoic time, and the eastern Brooks Range, which continued to be tectonically active through the Quaternary (Grantz and others, 1994). The abrupt northern flank of the central Brooks Range, which trends east-west, is intersected by major north-trending glacial valleys spaced at intervals of about 100 km. During each late Cenozoic glacial episode, alpine glaciers of the north-central Brooks Range reoccupied their deep bedrock valleys and flowed north from the range front between pairs of massive compound lateral moraines as much as 300 m high (e.g. Hamilton, 1979a, 1980). Because of the thick, continuous permafrost, which underlies this region, the moraines must be nearly as resistant as bedrock, and younger glacial advances seldom breached them.

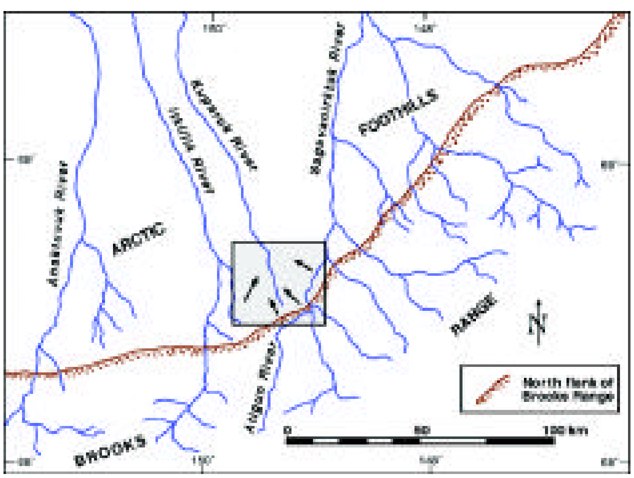

Figure 1. Itkillik-Sagavanirktok Rivers region, showing change in trend of the northern flank of the Brooks Range and asymmetric development of the Sagavanirktok drainage system. Arrows show glacial flow directions into the upper Kuparuk River region (shaded rectangle).

The relative extent of successive drift sheets in neighboring valleys of the north-central Brooks Range provides a measure of drainage changes with time (Figure 2). This pattern, which reflects the relative volumes of alpine glaciers, indicates that the major valleys progressively pirated their neighboring drainages to become dominant during the course of the Quaternary. The intervening glacial valleys, which initially supported large glaciers, progressively lost glacial discharge as their headwaters were captured by the master valleys; they supported only small glaciers during late Quaternary time.

In contrast, the eastern Brooks Range was subjected to northward-verging thrust faulting and associated detachment faulting that continued through the Quaternary

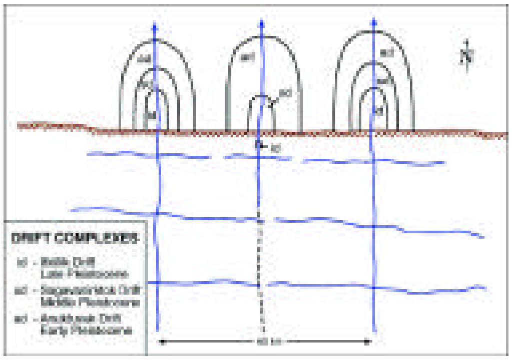

Figure 2. Drift distributions mapped along the north flank of the Brooks Range (Hamilton, 1978, 1979a, 1980), showing how extent of successive drift sheets reflect Quaternary drainage evolution in the north-central Brooks Range. Two master valleys have progressively captured drainage from the intervening valley system by headward erosion of tributaries along east-west-striking belts of erodible rock. The three valleys supported glaciers of comparable size during early Pleistocene time, but by late Pleistocene the middle valley was a relatively small glacial drainage network.

up to the present day (Grantz and others, 1994). The drainage patterns of this region consequently are less regular, and the drainage history is more complex. Near the upper Kuparuk River area, the range front abruptly changes to a northeasterly trend (see Figure 1). The strongly asymmetric Sagavanirktok drainage system, which is dominated by its eastern tributaries, contrasts markedly with the more regular drainage networks farther west. The glacial history, as recorded by drift sheets of differing ages, also shows less regularity (Figure 3).

On a smaller scale, some of the complex glacial geology of the upper Kuparuk River region is due to the influence of permafrost. The active layer (the seasonally thawed layer above the permafrost) ranges in depth from 25 to 30 cm in poorly drained deposits beneath thick moss and sod cover to over a meter in permeable coarse-grained sediments (Munroe and Bockheim, 2001). The permafrost table is deeper beneath water bodies, and may lie at several tens of meters depth beneath the largest, deepest lakes of the map area and beneath deep channel segments of the Sagavanirktok River. Although exact thickness of the permafrost is uncertain, records from other parts of the northern Brooks Range and Arctic Foothills (e.g., Ferrians, 1965; Williams, 1970, Brown et al, 1997) suggest that its base probably occurs at about 150-250 m depth.

Glacier ice, which stagnated beneath thick glacial deposits after the close of the Pleistocene, may be preserved as "permafrost" under some circumstances. Glaciers with ice exposed at the surface or covered by only a thin debris layer would have continued to downwaste. As the ice

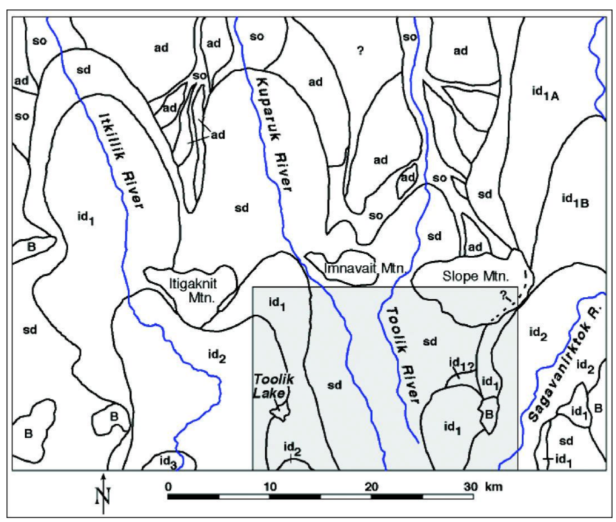

Figure 3. Glacial deposits of areas adjacent to the Kuparuk River region. Note contrast between nested drift sheets of the Itkillik River valley and less regular drift distributions farther east. Unit ad is drift of Anaktuvuk River age (see map insert and Appendix for all other unit designations). Shaded rectangle is the northern part of upper Kuparuk River map area.

thinned, however, its debris load would have accumulated and thickened at the surface, and the rate of downwasting consequently would have decreased. Thick debris cover would have allowed relict glacier ice to persist beneath an active layer that thawed each summer, and thus became part of the local permafrost. One indication of persisting subsurface glacier ice is the presence of kettle lakes that continue to enlarge today (Hamilton, 1982a; see cover photos). Such kettles have unvegetated, unstable flanks that steepen downward to near-vertical slopes at water level or that are broadly subject to slump and flowage. Their water generally is turbid owing to abundant fine mineral sediment held in suspension. Two kettles of this type have been identified in the upper Kuparuk area (Plate A), and others have been mapped at similar positions at the north flank of the Brooks Range farther to the west (Hamilton, 1982a). Relict glacier ice may be widely present in the continuous permafrost zone, having been reported from the Canadian Arctic (Fujino et al., 1988; St. Onge and McMartin, 1989), northern Greenland (Houmark-Nielsen et al., 1994), and northern Siberia (Astakhov, 1992; Astakhov et al., 1996; Vaikmae et al., 1993).

Near-surface permafrost also promotes solifluction, which is slow flowage of soil that occurs in the active layer during the annual thaw season. Solifluction is most widespread during spring and early summer, when the active layer generally is saturated with moisture that is released by thawing but remains confined above the surface of impermeable permafrost. Movement rates up to 5 cm per year are common on solifluction slopes, but more rapid rates up to 10 or even 15 cm per year have been recorded at some sites (Washburn, 1980, p. 208-213). Widespread solifluction in the upper Kuparuk River area has obliterated some of the older glacial deposits, especially those that occur on steep slopes or at their bases.

REGIONAL GLACIAL SEQUENCE

The basic glacial sequence for the central Brooks Range was defined by Detterman and others (1958), with modifications by Porter (1964), Hamilton and Porter (1975), and Hamilton (1986), (Table 1). Drift of four major glacial intervals is recognized in the valleys of the Itkillik and Sagavanirktok rivers (Hamilton, 1978, 1979c); these valleys are the type localities for two of the glaciations (Detterman, 1953). The oldest two advances, termed Gunsight Mountain and Anaktuvuk River, are inferred as to date from late Tertiary and early Pleistocene time, respectively (Hamilton, 1978, 1986, 1994). Drift sheets assignable to these glaciations are widespread north of the Brooks Range, but near the range front they have been overlapped by younger glacial deposits or eroded on steep slopes. Neither drift is recognized in the upper Kuparuk River area. The next younger glacial advance, the Sagavanirktok River glaciation, is believed to be a complex of glacial events dating broadly from middle Quaternary time (about 780,000 to 125,000 yr B.P.). The drift of Sagavanirktok River age locally forms two units that contrast in postglacial modification and probably were separated by a major interglaciation.

The youngest Pleistocene glacial advances were included within the Itkillik glaciation by Hamilton and Porter (1975), who subdivided this sequence into Itkillik I and Itkillik II

Table 1. Glacial sequence in the central Brooks Range. Modified from Hamilton (1994).

Age	Glaciation	Phase
Holocene	Neoglaciation	-------
Late Pleistocene	Itkillik II	Latest Itkillik II readvance (id_3) Younger advance (id_{2B}) Older advance (id_{2A})
	Itkillik I	Phase B (id_{1B}) Phase A (id_{1A})
Middle Pleistocene	Sagavanirktok River	Late phase (sd_2) Main phase (sd_1)
Early Pleistocene	Anaktuvuk River	--------
Late Tertiary	Gunsight Mountain	--------

advances. Two glacial advances of Itkillik I age and two during Itkillik II time are currently recognized in the Brooks Range (Hamilton, 1986, 1994). Itkillik I advances occurred more than 53,000 ^{14}C yr B.P. They are believed to be younger than the last interglacial maximum (isotope stage 5e). In some major valleys, Itkillik I drift sheets are divisible into two subunits (termed IA and IB) that contrast in postglacial modification and therefore may differ significantly in age. The subsequent Itkillik II advances occurred between about 25 and 11.5 ka (ka: thousand years before present) and are broadly contemporaneous with the major late Wisconsin advances of the standard North American glacial succession (Hamilton, 1982b, 1994). A late Itkillik II readvance is recorded in many valleys of the central Brooks Range (Hamilton, 1986, p. 37-38). It is bracketed by radiocarbon dates of about 12.8 and 11.4 ka near the east end of Atigun Gorge (Hamilton, 1996, p. 30-33).

Late Holocene glacial deposits, assigned to the Neoglacial interval of Porter and Denton (1967), are common at altitudes above about 1500 m in cirques and valley heads south of the upper Kuparuk area (e.g. Ellis and Calkin, 1984). The nearest of these features occurs about 13 km beyond the south margin of the map in this report.

SAGAVANIRKTOK RIVER GLACIATION

MAIN PHASE

During Sagavanirktok River time, large valley glaciers flowed north along the Itkillik, Kuparuk, and Sagavanirktok River drainages to reach outer limits about 50-60 km beyond the north flank of the Brooks Range (see Figure 3). A smaller lobe, its terminus centered on the Toolik River, extended only about 8 km north of Slope Mountain. The Itkillik and Sagavanirktok lobes probably were fed by drainage networks much like those of today, but the source of the Kuparuk lobe is obscure. The Kuparuk glacier was nearly as large as that in the Itkillik valley, judging from the comparable sizes and northward extents of their drift sheets and the comparable sizes of their outwash trains. The Kuparuk ice stream probably was fed by the Atigun River valley, and may reflect a time before that valley's head was captured by south-flowing drainage systems or its eastern tributaries were pirated by the upper Sagavanirktok River drainage (see Figure 1). The small size of the Toolik River lobe probably indicates that its mountain source areas had been largely captured by neighboring drainages by middle Pleistocene time.

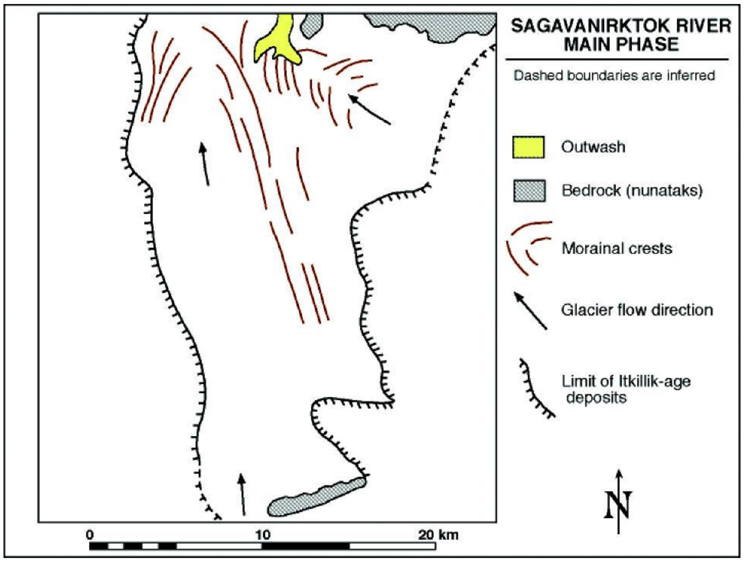

Figure 4. Drift of Sagavanirktok River main phase in upper Kuparuk River map area. Hachured lines show extent of subsequent overlap by glaciers during Itkillik time.

Drift of the Sagavanirktok River main phase (sd_1) occurs through the central part of the upper Kuparuk River area (Plate A and Figure 4). It is overlapped by younger glacial deposits to the east and west; to the north it is obscured by solifluction sheets on the steep flanks of Imnavait and Slope Mountains. To the south it generally is absent from the steep bedrock slopes north of Atigun Gorge, where initial deposits may have been relatively sparse and where erosion may have stripped most of them following glacier retreat.

The subdued landscapes of Sagavanirktok River age reflect a long interval of postglacial modification. Moraines typically are wholly vegetated (Walker and Walker, 1996); they have broad crests and gentle flanking slopes (Table 2). Crests and upper slopes have continuous cover of windblown silt (loess), but widely dispersed large erratic boulders protrude as much as a meter above the silt. Solifluction has redistributed much of the loess cover from upper to lower parts of moraine flanks. Ubiquitous horsetail drainages and a lack of stream channels indicate that solifluction probably is still active. Many of the swales between moraines contain thick bodies of ice-rich silt (unit si), within which small thaw ponds have developed. Kettle lakes are almost entirely absent, having been destroyed by erosion or filled by solifluction. Most drainages have silty channels with beaded thaw ponds along them. Even the largest stream, the upper Kuparuk River, meanders through a silty floodplain (unit al-s) that contains numerous thaw ponds.

The smoothly arcuate curves of Sagavanirktok River moraines, their nearly continuous crests (which extend unbroken for as much as 12 km), and their general occurrence as paired features indicate that they formed as lateral moraines and were subjected to only minor postglacial stream erosion. Their map pattern therefore must delineate two separate lobes of glacier ice in the present upper Kuparuk River area. The western lobe, the larger of the two, was centered on the present-day Kuparuk River near Imnavait Mountain, but farther to the south it primarily was situated west of the present river course. It probably was generated by a glacier that originated in Atigun valley; however, it continued north in part across the beveled uplands that form the north flank of Atigun Gorge near its west end. The eastern lobe, which is centered on the unnamed east fork of the Toolik River, probably was a northwest-flowing ice tongue that overflowed the west wall of the Sagavanirktok Valley.

LATE PHASE

Glacial deposits of apparent age intermediate between that of Sagavanirktok River and Itkillik drift (Plate A, unit sd_2, Figure 5) occur along the Kuparuk River near its head and also west of the Kuparuk River near the mapped outer limit of Itkillik drift. The deposits along the Kuparuk River clearly represent a much less extensive glacial advance that followed the Sagavanirktok River main phase after a long interval. The deposits west of the Kuparuk River may also date from this advance, but they may in part represent older drift of Sagavanirktok River age that was affected by later glacial meltwater. The meltwater may have "rejuvenated" the older deposits by stripping away the insulating cover of sod and silt, exposing gravel surfaces and causing buried glacier ice to melt.

Kuparuk River Locality

A set of closely spaced, slightly arcuate morainal ridges of the Sagavanirktok late phase glaciation occurs along the east side of Kuparuk River 9-13 km north of the northern flank of Atigun Gorge. Gravel terrace remnants, which may represent a former outwash train, originate near the northernmost ridge and extend along both sides of the river for 2-3 km. The ridges have been largely obliterated by solifluction along the west side of the Kuparuk River, but faint breaks in slope appear to mark their former positions. The ridges appear to define a narrow glacial lobe, only 3-4 km wide, which retreated southward up the valley floor of the Kuparuk River. The ridges and outwash subsequently have been eroded along the river, leaving concentrations of coarse water-washed gravel (units io_1 and al-sg on Plate A). The moraines occupy the floor of a valley (about 180-200 m deep and perhaps 6 km wide) that was eroded by the Kuparuk River within the large moraines of the main phase of Sagavanirktok River glaciation following the retreat of those glaciers. They consequently are not only younger than the main-phase moraines, but they probably formed during a separate glaciation. They extend beyond the mapped outer limits of Itkillik I glacier advances into the

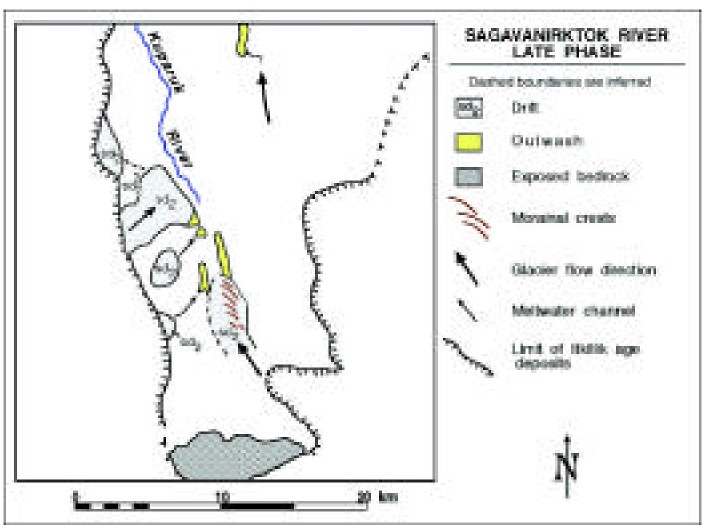

Figure 5. Drift and outwash remnants of the Sagavanirktok River late phase (sd_2) in the upper Kuparuk River map area. Hachured lines show extent of subsequent overlap by glaciers during Itkillik time.

upper Kuparuk River valley, and they probably also were eroded by meltwater from that glacier lobe (see the following section); they therefore are older than the Itkillik I advance. Because of their extensive obliteration by solifluction, they are considered to be closer to Sagavanirktok River than to Itkillik age, and they probably represent a separate later advance of middle Pleistocene age. Similar deposits have been mapped as “Drift of Younger Sagavanirktok River Age" farther west in the Brooks Range (Hamilton, 1979a, 1980).

Areas West of Kuparuk River

Drift intermediate in appearance between Sagavanirktok River and Itkillik deposits occurs in four localities west of the Kuparuk River. The deposits lack the

Table 2. Characteristics of drift of Sagavanirktok River, Itkillik I, and Itkillik II age, Itkillik valley region. From Hamilton (1986).

	Sagavan-irktok River (end Moraine)	**Itkillik I**			**Itkillik II**	
		End moraine	**Lateral moraine**	**Kame field**	**End moraine**	**Kame field**
MORPHOLOGY						
Crest width (m)	100-200	5-10	6-8	--	4-5	2
Maximum slope angle (^{o})	2.5-3	15	21	20	17	17.5
Irregularities per 200 m	0	7	6	17	8	8
WEATHERING (* denotes very stony surface, but most stones are smaller than boulder size)						
Boulders per 250 m^2	1-5	197	--	58*	203	121*
Boulder protrusion (% of diameter)	5-20	25	50	50	40-60	>50
Soil color, maximum	10YR 4/4	7.5YR 3/2	--	--	10YR 4/3	10YR 4/2
Weathering rinds (mm)	--	0.5-1.5	.4	1.3	0.5-1.0	0.5-1.5
CAST LITHOLOGY %						
Kanayat Conglomerate						
Conglomerate facies	78	64	56	80	40	55
Sandstone facies	15	33	25	20	35	40
Ferrug. sandstone	7	trace	0	0	0	0
Nanushuk Formation	0	2	15	0	16	5
Lisburne Group limestone	0	1	4	0	9	0
VEGETATION						
Cover %	100	--	50	85	80	80
Composition	Tussock tundra	Mixed Tussock tundra and *Dryas* heath			*Dryas* heath	

broad sweeping moraines, smooth flanking solifluction slopes, and broad silt-filled depressions that are typical of Sagavanirktok-age deposits. Kettles are present, but these are more widely scattered and more modified by solifluction than typical kettles of Itkillik age. The four deposits could form part of a once-continuous drift sheet that overlapped the Kuparuk drainage divide from the west and that later was partly obliterated by solifluction on steep slopes and dissected by meltwater streams of Itkillik I age. Alternatively, some of the kettles and irregular relief possibly could have formed when meltwater streams of Itkillik age eroded insulating vegetation, sod, and sediments that overlay relict glacier ice that had persisted from the Sagavanirktok River main phase.

ITKILLIK I GLACIATION

During the maximum recognized advance of the Itkillik glaciation, valley glaciers flowed north through the deep bedrock troughs now occupied by the Itkillik, Atigun, and Sagavanirktok Rivers. Beyond the range front, glacial lobes in the Itkillik and Sagavanirktok valleys were of similar widths (12 and 14 km, respectively), and they extended comparable distances (40-50 km) beyond the mouths of their mountain valleys. The glacier that flowed north from Atigun valley was significantly smaller than its neighbors (see Figure 3), and it extended only 27 km north of the range front. It may have been deflected northeast into the Kuparuk drainage system by contact with the larger glacier in the Itkillik valley.

The irregular drift of Itkillik I age has been much less modified by postglacial weathering and erosion than the smoother and more regular Sagavanirktok-age moraines (Table 2). However, it exhibits postglacial modification on a smaller scale. Moraine crests are 5-10 m wide and they typically are slightly flattened; their surfaces commonly bear frost hummocks, frost boils, and secondary and tertiary polygons as described by Black (1976, p. 6-7). Erratic boulders are more abundant here than on the surface of older drift. Many boulders have disintegrated down to ground level, but others protrude by as much as half of their diameters. Rock types preserved on the moraines are more variable than on the older glacial deposits. Vegetation cover is less continuous and more variable than that on moraines of Sagavanirktok River age (Jorgenson, 1984, Walker and Walker, 1996), and topographic

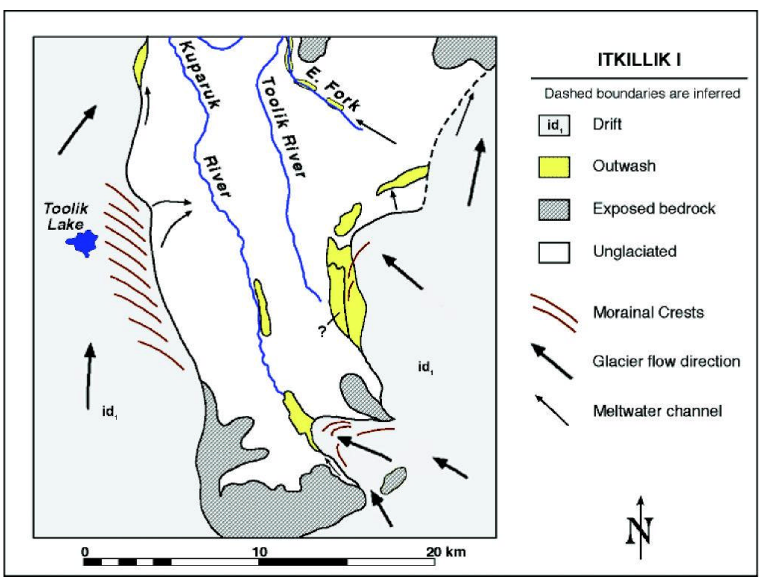

Figure 6. Drift and outwash of Itkillik I phase in the upper Kuparuk River map area. Present-day Toolik Lake is shown for reference.

crests typically have discontinuous cover of heath plants. Patches of bare gravel and shattered boulder fragments are common along the crests of moraines and isolated hillocks. Lower slopes and swales are covered with silty solifluction deposits, but they lack the thick accumulations of ice-rich silt that are present on older glacial deposits.

Drainage features also differ markedly from those of Sagavanirktok River age. Kettles generally are present. They are subrounded to subangular in outline, with grassy flanks and marshy shores that have developed on accumulating aprons of soliflucted silt. Most kettles are connected by small streams. Drainage nets are well integrated, but they are largely controlled by primary drift morphology. For example, arcuate stream courses occupy depressions between lateral moraines, and other streams flow from the drift margin along channels carved by former meltwater drainage.

Glaciers of Itkillik I age did not extend into the central part of the upper Kuparuk River area, but they flowed into its western, eastern, and southern sectors (Plate A and Figure 6). The glacier from Atigun valley flowed north along the edge of the upland now occupied by the upper Kuparuk River. Its outer limit is poorly defined on the steep bedrock slopes north of Atigun Gorge, but farther north it begins to form recognizable lateral-moraine segments at an altitude of about 1050 m. The drift limit is traceable northward for 24 km to the margin of the map, declining progressively to about 650 m asl. In the southern part of the map area, the outermost glacial deposits commonly overlie bedrock; farther north, they form a free-standing end moraine as much as 200-250 m high.

Following its advance, the outer sector of the glacial lobe probably stagnated because its irregular kame-and-kettle topography lacks recognizable recessional moraines. East and southeast of present-day Toolik Lake, however, dynamic ice retreat is indicated by at least 14 closely nested lateral moraines. These are separated by slightly arcuate drainage swales, along former ice-marginal meltwater channels.

A second glacial lobe of Itkillik I age entered the eastern part of the map area from the Sagavanirktok valley. Glacier ice overflowed the valley wall at about 900 m altitude north of Atigun Canyon and formed a lobe that spread westward for at least 5.5 km into the headwaters of the Toolik River. It formed an irregular deposit with abundant kettles (unit id_1) that is flanked to the west by a belt of outwash gravel up to 2 km wide (unit io_1). The alignment of linear topographic highs on the outwash with morainal landforms on the drift lobe suggests that the glacial lobe must have been more extensive than its present surface morphology indicates. As the glacier began to recede, its deposits were eroded by meltwater concentrated between the ice front and the ridge flank to its west. A higher-level water-scoured surface on that ridge may have formed when the ice was at its maximum extent (unit (io_1)).

Although a few eroded remnants may be present, very little Itkillik I drift is recognized north of the drift lobe described above. This area has been severely impacted by meltwater that was confined between glacier ice to the east and the steep face of Slope Mountain to the west.

The east fork of the Toolik River may have transported meltwater during Itkillik I time, but down a gradient too steep to allow significant outwash deposition. The incised channel of that stream differs from the silty valley fills of the Toolik River's main branch and of the Kuparuk River. Solifluction along the east fork is also much more limited than that along the other drainages. Although the east fork crosses drift from Sagavanirktok River age, surface sediments, vegetation, and morphology near its channel may resemble those of Itkillik I age more closely. Some outwash of Itkillik I age probably occurs along the east fork, but the more extensive outwash-terrace remnants near the north margin of the map area (see Figures 4 and 5) probably are Sagavanirktok-age features that were exhumed during Itkillik I time.

Ice of Itkillik I age also spilled over the north wall of Atigun Gorge near its east end and extended west-northwest for 7 km into the head of the Kuparuk drainage. Several arcuate, nested end moraines bordered by ice-marginal meltwater channels mark the former terminal zone. A sharply defined moraine about 2.5 km farther upvalley (unit id_{1B}) may represent a younger readvance of Itkillik I age. An outwash apron originates at the outer moraine and is traceable for several kilometers down the present course of the Kuparuk River before it gradually merges with the silty valley-floor deposits farther north. However, about 12 km beyond the limit of recognizable outwash, drift of Sagavanirktok River late phase has been scoured along its inner flank, leaving a water-washed stone pavement (unit io_1). This surface may have been eroded by meltwater from the Itkillik I glacier.

ITKILLIK II GLACIATION

The glacier flow pattern of Itkillik II time was similar to that of Itkillik I glaciation. Glaciers entered the map area from the mountain valleys of the present-day Itkillik, Atigun, and Sagavanirktok rivers (see Figure 3). The Itkillik valley and Sagavanirktok valley lobes were of about comparable size, but the much smaller Atigun lobe extended only 11 km beyond the range front. Drift limits of Itkillik II age are marked by sharp moraine fronts that rise above the heads of conspicuously channeled outwash aprons. Drift surfaces are more irregular, stonier, less vegetated, and lithologically more varied than those of Itkillik I age (see Table 2).

Moraines of Itkillik II age have sharp crests and steep flanking slopes. They retain minor surface features such as cross-cutting meltwater channels, multiple crests, and small ridges or benches along their flanks; and they have first-generation ice-wedge polygons with sharp margins. Vegetation is *Dryas* heath, with dwarf willows and dwarf birches present in the deepest swales (Walker and Walker, 1996). Soils are less well developed than those on deposits of Itkillik I age (Munroe and Bockheim, 2001). Surface boulders commonly protrude to half or more of their diameters and to heights of 60-80 cm. Solifluction occurs only locally on lower slopes, and most upper slopes lack colluvial cover. Channeled outwash surfaces generally have only a thin (about 0.3 m) cover of frost-mixed gravel and silt. Narrow solifluction sheets are beginning to encroach on their edges, but many drainage swales still retain their original gravel floors. Surface drainage is poorly integrated, and many kettles are isolated from streams. Kettles have flanking slopes close to angles of repose; they have angular to sub-angular outlines, and many retain extreme irregularities such as peninsulas and islands. Their shores are partly vegetated, with bare gravel exposed around much of their perimeters. Some kettles are still actively forming, as demonstrated by bare, unstable flanks, open tension cracks, and turbid water; and by active flows or slumps along their banks.

Much of the drift of Itkillik II age in the Itkillik-Sagavanirktok valley area forms massive ice-stagnation deposits that lack clear recessional features. However, evidence for two readvances is widely present (Figures 7 and 8).

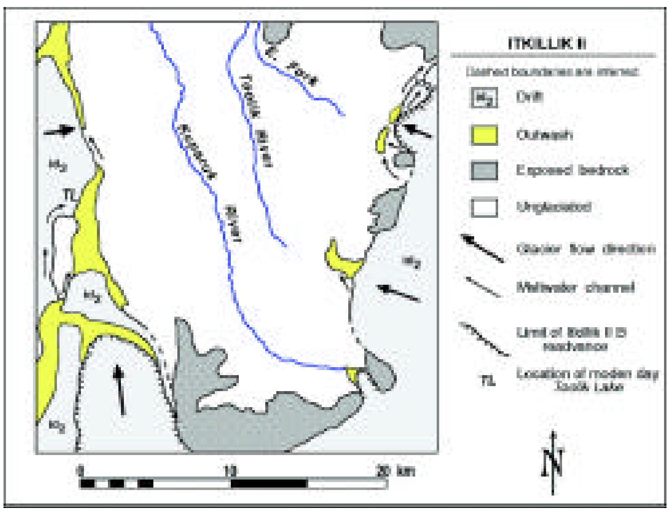

Figure 7. Drift and outwash of Itkillik II phase in upper Kuparuk River area. Hachured lines show extent of phase IIB readvance where recognized. *TL*, location of present-day Toolik Lake.

ITKILLIK VALLEY LOBE

Within the Itkillik valley north of the range front, the glacier of Itkillik II age divided into two lobes that flowed northwest and northeast past the south flank of Itigaknit Mountain (see Figure 3). The eastern lobe extended into the area north and west of present-day Toolik Lake (Figure 7), where it formed extensive ice-stagnation deposits with numerous irregular kettles (unit id_2).

Water-washed deposits of sandy gravel form ridges, flat-topped mounds, and irregular bodies (unit im_2) within the drift complex. These features probably were formed by meltwater that flowed beneath the stagnating glacier, and perhaps later occupied ice-walled open channels as the glacier continued to thin. A major meltwater outlet forms the east shore of Toolik Lake and extends northeast from the lake into a narrower channel that skirts the east end of the drift complex. Farther north this drainageway feeds into an outwash train (unit io_2), 2.5 km wide near its apex, that extends beyond the north margin of the map area. Toolik Lake clearly could not have existed when this meltwater system was active; it must have formed later by melt-out of stagnant glacier ice that was buried beneath the meltwater deposits.

ATIGUN VALLEY LOBE

Despite the unusually subdued appearance of its outermost drift, drainage relationships indicate that the glacier of Itkillik II age that originated in Atigun valley must have extended to within 4 km of present-day Toolik Lake. Two subsequent readvances of the glacier formed unusual drift lobes that are less extensive than the outer lobe but stand 100 m or more above it.

The drift of the outermost Atigun lobe is more vegetated and less stony than that north and west of Toolik Lake, and its kettles are more rounded. However, a broad outwash train that originates at the north limit of the drift complex extends north to Toolik Lake and merges smoothly with the outwash from the larger Itkillik valley lobe. Outwash that partly originates from the Itkillik valley lobe also skirts the west flank of the Atigun lobe and merges with the Atigun outwash apron. These relations show that the Itkillik and Atigun lobes must be of comparable age. The more subdued nature of the Atigun lobe may be due to unusually thick loess cover, which reflects an abundant silt source in the extensive late-glacial and postglacial lake beds along its valley floor south of Galbraith Lake (Hamilton, 1978). If similar lake beds formed at the close of Itkillik I glaciation, large amounts of lacustrine silt and fine sand might have been eroded by the advancing glacier of Itkillik II age and incorporated in its drift. Abundant fines within the drift also would contribute to its subdued appearance.

A later readvance of the Itkillik II glacier terminated 5 km farther south. It formed a steep-fronted drift sheet (unit id_{2B}) that stands about 100-150 m above the older drift surface and has more local relief. Several kettles on the drift sheet have turbid water and steep unstable flanks; they evidently are still enlarging today. Meltwater at the terminus of this drift sheet formed an outwash train that extends westward to merge with the regional meltwater system. At the front of the drift lobe, outwash remnants persist as only a narrow rim around a large, deep kettle with unstable flanks (unit f_1). Residual glacier ice must have been present at the time of outwash

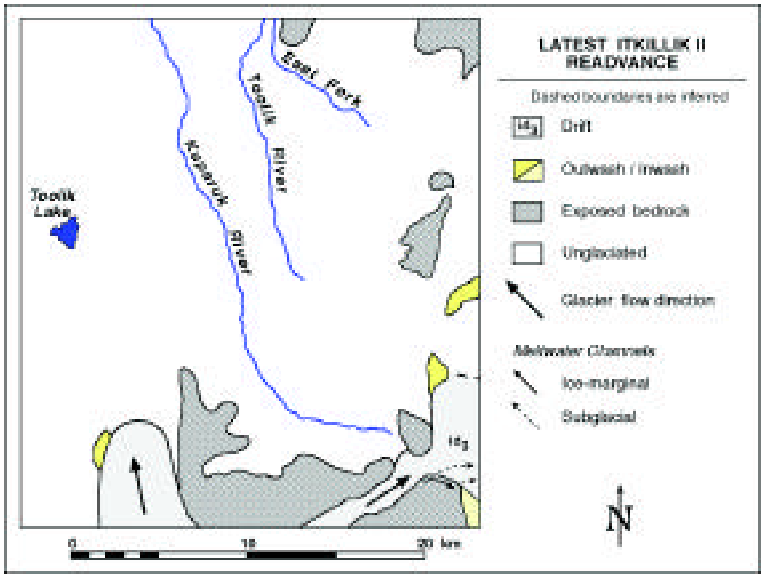

Figure 8. Drift and outwash of latest Itkillik II readvance in upper Kuparuk River map area. Unit ii_3 is inwash against Atigun Valley Lobe.

deposition, and it may still be melting out today.

During a later, final readvance, the Itkillik II glacier in Atigun valley formed two lobes which flowed north and east from the area of present-day Galbraith Lake (Figure 8). The northern lobe terminated 7 km north of the lake, forming a broad, smooth-surfaced, lobate deposit (unit id_3) that overlaps older drift of Itkillik II age. Despite its well documented young age (see next page), this drift sheet has a silty, vegetated surface, with broad crests, gentle slope angles, and sparse erratic boulders. It must contain abundant fine sediments derived by glacial erosion and postglacial wind scour from extensive lake beds in Atigun valley.

The eastern ice stream flowed east through the Atigun Canyon and spread into a small piedmont lobe on the floor of Sagavanirktok valley. Ice-marginal drainage channels that occur at altitudes up to 900 m near the mouth of Atigun Canyon decline eastward. They contact the heads of linear gravel deposits (unit im_3) that extend down the west wall of Sagavanirktok valley and probably were formed by subglacial meltwater. The piedmont lobe partly blocked the upper Sagavanirktok River, which deposited sandy "inwash" sediments that are dated as forming between 12,800 and 11,400 uncalibrated ^{14}C yr B.P. (Hamilton, 1979c, 1996).

SAGAVANIRKTOK VALLEY LOBE

Glacier ice of Itkillik II age expanded westward into the extreme eastern part of the map area (see Figure 3). The outermost glacial deposits east and south of Slope Mountain, which formerly were continuous with outermost Itkillik II drift in the Sagavanirktok valley center, have been partly eroded by meltwater. Farther south, the Itkillik II limit is poorly defined along the steep west wall of Sagavanirktok valley, but closer to Atigun Gorge the valley wall is lower and a narrow moraine is preserved along its crest. An outwash train and a meltwater channel originate at the moraine front and extend across older kettled drift deposits (unit id_1). A large kettle that obliterates part of the outwash train must have been formed by melt-out of buried ice (after glacial recession from the moraine of Itkillik II age caused outwash deposition to cease). A subsequent readvance of the Itkillik II glacier cannot be distinguished along the west wall of Sagavanirktok valley, but east and south of Slope Mountain the steep front of its deposits rises sharply above the water-scoured surface of the outermost Itkillik II drift. The younger drift sheet (unit id_{2B}) has the stony, boulder-littered, irregular surface characteristic of Itkillik II deposits, and its kettles have subangular outlines. Meltwater that issued from the readvancing glacier was confined between the ice front and the steep face of Slope Mountain, and it must have been highly erosive.

The final readvance of the Sagavanirktok valley glacier terminated about 22 km upvalley from the mouth of Atigun Canyon, and its deposits are not recognized in the upper Kuparuk River map area.

UPPER KUPARUK LOBE

Glacier ice of Itkillik II age overflowed the north wall of Atigun Gorge near its east end, reoccupying a U-shaped trough that may have been eroded initially by glaciers of Itkillik I age. Ice extended northwest for about 2 km from the gorge, terminating at about 950 m asl on the drainage divide that forms the present head of the Kuparuk River. The ice lobe evidently carried little debris, because its deposits form thin and discontinuous patches over local bedrock.

A second sparse concentration of glacial deposits crosses the floor of the U-shaped trough closer to the north wall of the gorge (see Figure 8). These debris are appropriate in altitude (about 900 m) for an ice limit of the youngest Itkillik II readvance, but this correlation is speculative.

HOLOCENE DEPOSITS

Through much of the upper Kuparuk River area, Holocene processes were a continuation of those active during late Pleistocene time. For example, solifluction continued to be at least intermittently active on slopes, and silty, ice-rich sediments continued to accumulate in swales and along the courses of sluggish small streams. In contrast, unstable conditions prevailed on the floors of valleys abandoned by glaciers at the close of Itkillik II time, where extensive Holocene deposits commonly formed.

SAGAVANIRKTOK VALLEY FLOOR

Modern alluvial gravel and gravelly floodplain deposits of the Sagavanirktok River (unit al_3) are flanked by a series of higher terraces. The highest terrace may in part be of glacial origin; the younger terraces are entirely fluvial.

Discontinuous remnants of the highest terrace (unit tg_1) occur along both sides of the Sagavanirktok River north of the Atigun River confluence. The terrace surface locally is flat, but elsewhere it is irregular and deeply kettled. It stands as much as 50 m above modern river level, with ice-contact sand and gravel exposed in river bluffs where the deposit stands highest. The 50-m terrace must have formed by interaction of the Sagavanirktok River with stagnant glacier ice along its valley floor, perhaps when the river was still carrying meltwater and outwash gravel from the late Itkillik II readvance of the Atigun piedmont lobe.

A younger river terrace (unit tg_2) stands 6-10 m high and has a smooth, well-drained surface that retains faint channel scars. Sparse shallow but subangular kettles indicate that some glacier ice was still present on the valley floor during its formation.

Modern floodplain and channel deposits of the Sagavanirktok River are designated al_3. They are flanked by slightly higher (ca. 2 m) floodplain surfaces (unit al_2) that have thicker silt and sand cover and are more continuously vegetated, but are conspicuously channeled. If still active, these surfaces probably are inundated only during major floods. A higher abandoned floodplain (unit al_1) is intersected by a probable kettle lake.

LOWER ATIGUN RIVER

Beyond the east end of Atigun Canyon, the lower course of the Atigun River flows across a broad alluvial-fan complex. Younger fan deposits (unit f_3) that border the modern stream course along its south side appear to be graded to the modern floodplain (unit al_3) of the Sagavanirktok River. Older-appearing fan deposits (unit f_2) north of the modern stream and fan appear to be graded to higher Sagavanirktok River floodplain levels (unit al_2 and perhaps al_1). The oldest fan deposit (unit f_1) stands about 5 m higher and occupies an extensive fan-shaped area that is 2.1 km wide at its outer margin. This fan remnant appears to be graded to terrace level tg_2 of the Sagavanirktok River. Two small fan remnants that may have formed synchronously with the oldest fan occur on the glacial deposits south of the Atigun River. They formed near the lower ends of subglacial meltwater deposits, and may represent continued meltwater activity from a glacier retreating westward up Atigun Canyon.

GALBRAITH LAKE AREA

During southward glacier retreat up Atigun valley, an elongate lake formed behind the moraine complex that encloses present-day Galbraith Lake. The lake expanded southward as the glacier retreated, and at its maximum it extended at least 18 km upvalley from Galbraith Lake's modern south shore (Hamilton, 1978). Lake beds dating from a higher lake stage (unit l_2) also extend at least 2.7 km north of the present lake. An older lake bed (unit l_1) appears to extend 1.5 km farther north across a flat-floored basin, but it is obscured, perhaps by a cap of eolian sediment. Several beach ridges (unit b) occur near the north end of these deposits.

A large alluvial fan-delta has built out into the west side of Galbraith Lake. An older, inactive segment of this deposit (unit fd), which is evident at the southwest corner of the map, probably formed when the lake was at a higher level.

CONCLUSIONS

The complex glacial pattern of the upper Kuparuk River map area was controlled by: (1) multiple source areas for the glaciers, (2) tectonism along the north flank of the Brooks Range, and (3) repeated glacial advances during middle and late Pleistocene time. Glaciers flowed into the area from the Itkillik River valley to the west, the Sagavanirktok River valley to the east, and the Atigun River valley to the south. This flow pattern changed from each glaciation to the next younger owing to probable uplift along the upper Kuparuk drainage and to incision of the Sagavanirktok River, which eventually pirated the Atigun River drainage through Atigun Canyon. Moraines of seven individual glacial advances or readvances are distinguished within the map area. These provide widespread surfaces that differ significantly from each other in topography, loess cover, drainage development, weathering and soil formation, and vegetation cover.

Because of continuous permafrost, buried glacier ice tended to persist after each advance, and subsurface ice may still be melting out today beneath drift sheets of Itkillik age. This complicates the age sequence of glacial landscapes and constitutes a hazard for engineering structures.

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APPENDIX

MAP UNIT DESCRIPTIONS

GLACIAL DEPOSITS

NOTE: Unit designations in parentheses indicate thin and discontinuous drift. These overlie bedrock unless otherwise specified.

Itkillik Glaciation (late Pleistocene)

id **Undifferentiated Itkillik Drift**. Unsorted to poorly sorted, generally nonstratified till. Consists of stones to boulder size in compact matrix of mixed finer sediment in which silt generally dominant. Contains local ice-contact deposits of moderately sorted gravel. Mapped only in Atigun Gorge and at southeast corner of map area.

id_3 **Drift of Latest Itkillik Readvance**. Till, as described above, with locally abundant ice-contact deposits of moderately sorted sandy gravel and gravelly sand. Forms lobate deposits north of Galbraith Lake and east of Atigun Canyon. Matrix ranges from clayey stony silt (Galbraith lobe) to silty sandy gravel (Atigun lobe). Age is approximately 12.8-11.4 ka.

id_2 **Drift of Itkillik Phase II**. Till and ice-contact deposits, as described above. Forms narrow-crested (3-5 m) end moraines, prominent knob and kettle terrain, and conspicuously channeled outwash trains. Flanking slope angles as steep as 18°-23°. Crests and upper slopes lack loess and solifluction cover, and exposed stones exhibit only slight weathering. Most swales lack solifluction deposits. Age is approximately 25-11.5 ka.

id_{2B} **Drift of Itkillik Phase II (Younger Advance)**. Till and stratified ice-contact deposits, as described above. Mapped north of Galbraith Lake and southeast of Slope Mountain, where older deposits of Itkillik II age have been overlapped by a younger readvance. Age is uncertain.

id_{2A} **Drift of Itkillik Phase II (Older Advance)**. Till and stratified ice-contact deposits, as described above. Locally eroded by meltwater that issued from **id_{2B}** glaciers. Age is approximately 25-17 ka.

id_1 **Drift of Itkillik Phase I**. Till and meltwater deposits, as described above. Irregular morphology. Moraine crests 5-10 m wide; flanking slope angles as steep as 15°-21°. Erratic boulders common, and topographic crests commonly have exposures of bare gravel. Severely eroded by meltwater and partly overlapped by thin solifluction sheets in some localities (e.g. south of Slope Mountain). Formed sometime between 120 and 50 ka.

Subunits id_{1A} and id_{1B} are clearly differentiated drift deposits of older and younger Itkillik I age near head of Kuparuk River. These may correlate with the Phase IA and IB glaciations of Itkillik I age recognized elsewhere in the Brooks Range (Hamilton, 1986, 1994).

Sagavanirktok River Glaciation (middle Pleistocene)

sd **Undifferentiated Drift of Sagavanirktok River Age**. Till and meltwater deposits, as described below. Mapped only east of Toolik Lake on west flank of Kuparuk River valley. Locally eroded by younger (Itkillik-age) meltwater, forming surface concentration of boulders. Elsewhere capped by thick loess and solifluction deposits (as described below).

sd_2 **Drift of Younger Sagavanirktok River Age**. Poorly sorted nonstratified bouldery till, probably with local patches of moderately well sorted gravel (meltwater deposits). Forms subdued morainal topography intermediate in character between that of Itkillik drift and that of older Sagavanirktok River age. Some ridge crests lack loess and solifluction cover; they expose weathered residual gravel (resistant lithologies from which finer sediments have been eroded). Occurs just beyond limits of Itkillik drift.

sd_1 **Drift of Older Sagavanirktok River Age**. Till and meltwater deposits, as described above; entirely covered by eolian silt (loess) on ridge crests and by stony silt and organic silt (solifluction deposits) on flanking slopes. Forms distinct but very subdued nested morainal ridges 50-100 m high, with crests 150-300 m wide and flanking slopes generally 2°-4°. Large erratic boulders sparsely scattered on moraine crests and upper slopes.

GLACIAL OUTWASH DEPOSITS

Itkillik Glaciation

io_3 **Outwash of Latest Itkillik Readvance**. Moderately well sorted sandy gravel. Generally lacks loess or peat cover, and oxidized to only 20-30 cm depth. Occurs in front of, or marginal to, drift lobes of latest Itkillik II readvance.

io_2 **Outwash of Itkillik Phase II**. Sandy gravel, as described above. Stones etched, fractured, and pitted to 30-40 cm depth; oxidized to 30-45 cm depth. Forms extensive aprons and valley trains in front of or marginal to Phase II moraines. Subunit **(io_2)** is thin and discontinuous outwash along discharge channel of Itkillik II age that is scoured into older drift of Itkillik age.

io_{2B} **Outwash of Itkillik Phase II (Younger Advance)**. Sandy gravel, as described above, associated with front of **id_{2B}** drift sheet.

io_1 **Outwash of Itkillik Phase I**. Sandy gravel, as described above, generally with thin to moderate (0.3 to 2.5 m) loess and solifluction cover. Upper 1-1.5 m oxidized, with silt illuviation and weathered stones. Subunit **(io_1)** is thin and discontinuous outwash above lag concentration of older coarse gravel; mapped along sector of upper Kuparuk River valley floor that contains drift and outwash of Younger Sagavanirktok River age.

io_{1B} **Outwash of Itkillik Phase I (Younger Advance)**. Sandy gravel, as described above. Associated with glacial deposits of younger Itkillik I age near head of Kuparuk River.

Sagavanirktok River Glaciation

so **Outwash of Sagavanirktok River Age**. Moderately well sorted and stratified oxidized sandy gravel. Forms terrace remnants along Toolik River near north margin of map.

so_2 **Outwash of Younger Sagavanirktok River Age**. Sandy gravel, as described above, deposited during late Sagavanirktok River time. Forms valley train along Kuparuk River beyond **sd_2** drift sheet. Also fan-shaped deposits along west side of Kuparuk River at distal ends of northeast-trending meltwater channels that originate at limits of **sd_2** drift sheets.

Ice-stagnation Deposits

ii_3 **Inwash Deposits of Latest Itkillik Readvance**. Stratified sand and sandy gravel containing rooted grasses and willow shrubs. Deposited by Sagavanirktok River against upvalley flank of piedmont lobe from Atigun Gorge during latest Itkillik II readvance.

im_3 **Subglacial Meltwater Deposits of Latest Itkillik Readvance**. Moderately well sorted and stratified sandy gravel, with sparse boulders and some inclusions of poorly sorted till. Forms linear belts of unusually well drained and irregular topography within drift lobe of latest Itkillik II age near east end of Atigun Canyon.

im_2 **Subglacial Meltwater Deposits of Itkillik II Phase**. Sandy gravel, as described above, within drift of Itkillik II phase near Toolik Lake.

RIVER DEPOSITS

al **Undifferentiated Alluvium**. Gravel and sandy gravel along modern channel of the Toolik River. Flanked by vegetated floodplain deposits consisting of weakly stratified to unstratified sand and silt beneath silty peat and sod.

al_3 **Modern Alluvium**. Channel and floodplain deposits, as described above, along modern course of Sagavanirktok River.

al_2 **Low Floodplain Deposits**. Channel and floodplain deposits of Sagavanirktok River, as described above, mantled with up to 1.5 m of silt, sand, or peat, and generally vegetated.

al_1 **Higher Floodplain Deposits**. Channel and floodplain deposits of Sagavanirktok River, as described above, probably with 1-2 m mantle of silt and ice-rich silt.

al-s **Silty Alluvium**. Thick and continuous floodplain deposits of silt, organic silt, and ice-rich silt; with numerous thaw ponds. Overlie channel deposits that range from gravel and sandy gravel to silt with sparse sand and fine gravel. Grades southward into gravel deposits with thinner silt cover (subunit **al-sg**). Mapped only along upper Kuparuk River.

tg **Undifferentiated Alluvial Terrace Deposits**. Alluvial gravel and bouldery coarse gravel. Forms isolated deposit at mouth of unnamed eastern tributary to Kuparuk River near north margin of map.

tg_2 **Low Alluvial Terrace Deposits**. Fluvial sand and gravel, forming terrace 6-10 m above modern level of Sagavanirktok River. May bear cover of eolian silt 0.5-1.0 m thick.

tg_1 **Higher Alluvial Terrace Deposits**. Fluvial and ice-contact sand and gravel; well sorted to moderately sorted, with collapse structures common. Forms irregular to smooth kettled surfaces 25-50 m above modern level of Sagavanirktok River.

FAN DEPOSITS

f_3 **Modern Fan Deposits**. Moderately sorted and stratified sandy gravel. Locally bears thin cover of sand or silty sand that is capped by sod. Mapped only along lower course of Atigun River.

f_2 **Older Fan Deposits**. Sandy gravel, as described above, beneath thicker and more continuous cover of vegetated sand and silt.

f_1 **Oldest Fan Deposits**. Sandy gravel beneath sand and silt, as described above. Stands about 5 m above younger Atigun River fan deposits, and may be capped by eolian silt beneath thick and continuous sod cover.

fd **Fan-Delta Deposits**. Fan deposits of coarse gravel, as described above, that grade distally (downslope) into sandy lacustine deposits. Mapped only along west side of Galbraith Lake.

f-i **Inwash**. Moderately sorted and stratified sandy gravel. Mapped only 5-7 km south-southeast of Toolik Lake, where it forms fan-shaped accumulations against outer flank of end moraine of the Itkillik II age.

LACUSTRINE DEPOSITS

l_2 **Lacustrine Deposits (Younger)**. Well-sorted silt and sand, stratified where not disturbed by frost action. Has flat, poorly drained surface with thaw lakes and ice-wedge polygons. May grade locally into beach deposits of sand and sandy fine gravel. Mapped only at north end of Galbraith Lake.

l_1 **Lacustrine Deposits (Older)**. Probable silt and sand deposits, as described above, obscured beneath possible cap of eolian sand and silt. Beyond north end of Galbraith Lake.

b **Beach Deposits**. Slightly sinuous, steep-sided and sharp-crested ridges of sand and fine gravel, probably formed by combined wave and wind activity. Mapped only within unit ***l_1*** near north end of ancestral Galbraith Lake.

COLLUVIAL DEPOSITS

s **Solifluction Deposits**. Poorly sorted, nonstratified to weakly stratified stony sandy silt to organic silt. Forms sheets and aprons that thicken down slopes and accumulate up to several meters deep along slope bases. Forms widespread deposits on gentle to moderate slopes beyond limits of Itkillik-age deposits; locally present on Itkillik drift. Mapped as compound units (e.g. **s/sd**; **s/id**) where slope morphology suggests that glacial drift, although obscured by solifluction deposits, may occur at shallow depths beneath them.

si **Ice-rich Silt Deposits**. Ice-rich silt up to several meters thick, derived from airfall loess mixed with solifluction deposits. Fills elongate basins that generally lie along drainage swales. Sufficiently thick and extensive to constitute mappable units only on deposits of Sagavanirktok River age.

tr **Talus Rubble**. Angular, unsorted rock debris along lower face of Slope Mountain at extreme northeast corner of map. Areas of active talus are interspersed with more extensive vegetated talus that may be periglacial relict dating from Itkillik II glaciation.

fl_a **Active Tundra Earthflow**. Presently active debris flows and slumps on walls of enlarging kettles on glacial deposits of Itkillik II age north of Galbraith and Toolik Lakes

fl_i **Inactive Tundra Earthflow**. Flow and slump deposits, as described above, that are wholly vegetated and appear to be currently inactive.

BEDROCK

B **Bedrock**. As mapped by Brosgé et al. (1979), exposures along north margin of map area are dominantly Cretaceous rocks of Chandler Formation (conglomerate with interbedded shale and siltstone); those north of Atigun Canyon in southern part of map are conglomerate, sandstone, siltstone, and shale of Lower Cretaceous Fortress Mountain Formation. Exposed bedrock in the east-central part of the map is mostly Cretaceous shale, siltstone, and sandstone, with some Triassic limestone.

(B) **Near-surface Bedrock**. Bears generally thin mantle of talus, solifluction deposits, and sparse glacial erratics.

Bd **Bedrock Exposed by Human Disturbance**. Generally borrow-pit excavations.

CORRELATION OF MAP UNITS